(54) Title: MICROMECHANICAL SENSOR
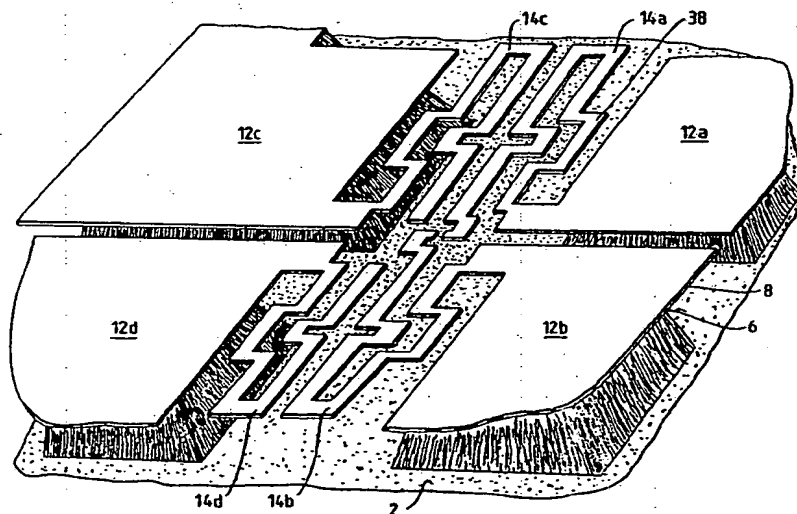
(57) Abstract

A micromechanical sensor has a plurality of sensing elements (14a-14d) which are supported at respective support regions (12a-12d). A first set of the sensing elements defines the sensing gap. In one arrangement this is defined by sensing elements supported by adjacent support regions. In another embodiment the sensing gap is defined between one sensing element and a reference beam formed by connection of the return legs of two diametrically opposed sensing elements. The sensing elements are substantially similar one to another and each sensing element comprises an outgoing elongate leg extending away from its associated support region and a return leg substantially parallel to the outgoing leg extending towards the support region. By providing sensing elements which are substantially similar in shape and arranged in this way, the effects of thin film stress are minimised.

MICROMECHANICAL SENSOR

The present invention relates to a micromechanical sensor, and particularly to an electromicromechanical sensor.

There exist several fabrication techniques specifically for manufacturing micromechanical structures. These techniques fall broadly into two categories: bulk micromachining and surface micromachining. Bulk micromachining involves sculpting a silicon substrate by means of chemical etchants whilst surface micromachining involves the use of deposition of thin films on a silicon substrate.

Bulk micromachining is a proven high volume production technique used to fabricate structures with precisely determined critical dimensions. However, surface-micromachined sensors have the advantage of being significantly smaller than bulk-micromachined sensors. Since film thicknesses on the surface of a silicon wafer can be as many as 100 times smaller than the thickness of a wafer itself, surface-micromachined parts can be an order of magnitude smaller than bulk-micro-machined parts. Futhermore, surface-micromachining techniques which involve the deposition and etching of films are more compatible with conventional integrated circuit manufacture processes.

Surface micromachining has been used to manufacture an accelerometer which is described in the technology section of Electronic World News of 9th September 1991. There have also been attempts to make sensors comprising free-standing micro structures, such as beams, which can be deflected electrostatically towards and away from other parts of the micro structure so as to control the size of a gap.

There is currently a desire to integrate sensors onto silicon integrated circuit chips to reduce fabrication costs, increase the reliability and to miniaturize the sensors as far as possible.

The current proposals for surface-micromachined sensors all
suffer from a common difficulty and that is the existence of
stresses which arise in the thin films which constitute the
suspended elements of the micro structures. These stresses
can cause suspended elements of the micro structure to bend
and twist out of the plane in which the gap is defined. This
has at least two disadvantages. In the first place, there is
no longer control over the size of the gap since it could now
have a dimension outside the plane within which it was
originally defined. In the second place, where the sensing
relies on the contact of the suspended element with another
part of the micro-structure, this contact may in fact not take
place if the element twists so that it is moving in a plane
outside that of the other part of the micro-structure.

The present invention seeks to overcome these difficulties.

According to the present invention there is provided a
micromechanical sensor comprising a plurality of sensing
elements supported on a substrate at respective support
regions, a first set of said sensing elements having
respective sensing portions and arranged to define a sensing
gap and a second set of said sensing elements forming a
counterpart set the sensing elements being substantially
similar one to another, and each sensing element comprising an
outgoing elongate leg extending away from its associated
support region and a return leg substantially parallel to the
outgoing leg extending towards the support region.

It is particularly advantageous if the support regions are
arranged in close proximity to one another and to the sensing
gap. Preferably the distance between the sensing gap and the
support regions, and between the support regions, is less than
the length of each sensing element, preferably substantially
less. The support regions are preferably arranged
symmetrically.

As the sensing elements in the counterpart sets are
substantially similar in shape to the sensing elements
defining the sensing gap, when the counterpart set are subject
to forces intended to cause movement of the sensing elements
any twisting or bending effects of stress affect both the
counterpart set and the sensing set equally so that the effect
on the sensing action itself is minimised.

In one embodiment, the first set of sensing elements comprises
sensing elements supported by adjacent support regions, the
return leg of each sensing element terminating in its sensing
portion and the sensing portions defining between them the
sensing gap. The second set of sensing elements likewise
comprises sensing elements supported by adjacent support
regions, the support regions supporting the sensing elements
of the second set being arranged opposite the support regions
supporting the sensing elements of the first set. In this
embodiment, one of the second set of sensing elements acts as
a control element to attract one of the first set and thereby
close the sensing gap.

In another embodiment, the first set of sensing elements
comprises sensing elements supported by support regions
diametrically opposed with respect to one another, the free
ends of the return legs of these sensing elements carrying the
sensing portions. The counterpart sensing elements are
supported by respective support regions also arranged
diametrically opposed to one another and perpendicularly with
respect to the support regions supporting the sensing elements
of the first set. The return legs of the sensing elements of
the counterpart set are connected to form a suspended beam,
which acts as a reference element. Each sensing portion
defines with the beam a sensing gap. A sensor according to
this embodiment can be excited magnetically.

Each leg of each sensing element can include a stepped region,
the stepped regions being arranged so as to maintain the

symmetry of the sensor. The stepped region lies in the plane
of the sensing element. Such portions are advantageous where
the sensor is formed by a method involving the etching of a
silicon substrate. Such etching occurs preferentially where
there are convex corners and the provision of stepped portions
provides more convex corners at which the undercutting
preferentially occurs.

Preferably, each sensing element comprises an insulating layer
and a conductive layer over the insulating layer. The
insulating layer can be for example silicon nitride and the
conductive layer can be for example a metal such as gold.

The sensing portions of the sensor can be provided with
additional sensing layers particular to an analyte to be
sensed.

For a better understanding of the present invention, and to
show how the same may be carried into effect, reference will
now be made, by way of example, to the accompanying drawings
in which:-

     Figure 1 is a diagrammatic plan view illustrating the
principles underlying the sensor;

     Figure 2 is a perspective view of a sensor in accordance
with one embodiment of the present invention;

     Figure 3 is a diagrammatic plan view of the sensor
modified for use as an accelerometer;

     Figures 4 and 5 are sections through the sensor at
different stages of its manufacture;

     Figures 6 to 8 are plan views of a part of the sensor
during steps in its manufacture; and

Figure 9 is a diagrammatic plan view of a modified
version of the sensor.

Figure 1 shows the principles on which the sensor is based.
There are four support regions 12a,12b,12c,12d which are
arranged symmetrically with respect to one another and are
physically close to one another. Each support region supports
a respective suspended element 14a,14b,14c,14d. The supported
regions and elements are electrically isolated from one
another. Each suspended element is substantially in the form
of an elongate U, that is with one leg 18 extending away from
the support region 12, a relatively short base 20 and a return
leg 22 extending back towards a central region of the sensor
between the support regions. The return leg 22 is
substantially parallel to the outgoing leg 18. The suspended
elements are formed in two sets. The first set 14a,14b are
referred to herein as the sensing set. Each element 14a,14b
of the sensing set has at the end of its return leg 22 a
sensing portion 24. The sensing portions 24a,24b terminate in
sensing tips 26a,26b which define a sensing gap 28. This gap
provides the measurement facility of the sensor as described
in more detail hereinafter. The gap can be of the order of
1um or smaller, limited only by processing technology.

The other set of sensing elements 14c,14d constitutes a
counterpart set which is substantially symmetrical with the
previous set. It is an important aspect of the present
invention that there is symmetry between the suspended
elements. This maintains alignment of the sensing elements of
the sensing set and the counterpart set when movement of the
elements occurs during sensing. In addition, any acceleration
forces affecting the chip affect all elements approximately
equally so the gap width is largely unaffected. The
importance of this feature is discussed further later in
relation to operation of the sensor. In the embodiment of
Figures 1 and 2, the ends of the return legs 22 of the
elements 14c,14d are left free.

Another important feature of the described embodiment is the
provision of the four support regions 12a,12b,12c,12d spaced
physically close one to another. The distance between the
suspended elements is thus kept to a minimum to enable the
potential difference required to create a desired electrical
field to be kept to a minimum. This minimises the effect of
thin film stresses in the suspended elements 14a,14b,14c,14d.
These support regions also provide electrical contacts of the
sensor to which a voltage can be applied during operation of
the sensor. It is also important to maintain the support
regions close to the sensing gap relative to the length of
each element as shown in Figure 1, again to minimise the
effect of thin film stresses.

Compensation for thin film stresses is also provided by the
elongate U structure of the sensing elements, the legs of
which permit stresses to be accommodated in a direction
perpendicular to that in which sensing takes place. Thus, the
effects of stresses in the thin film which constitutes these
suspended elements have a negligible effect on the sensing
portions and the gap defined therebetween. Any effects
arising from this film stress is nullified by the symmetry of
the sensor and all the elements will be similarly affected.

Figure 2 shows another embodiment of the invention, in a
perspective view. Figure 2 shows a silicon substrate 2 which
provides the support regions 12a-12d for the suspended
elements 14a-14d of the sensor. Each element comprises a
layer 6 of an insulator such as silicon nitride and a layer 8
of a metal such as gold. These layers also define the
electrical contacts.

There will now be described a method of manufacture of the
sensor, with reference to Figures 4 to 8.

There is deposited on a (100) oriented silicon substrate 2 a
layer 6 of an insulating material such as silicon nitride to a
thickness of about 1 micron. In another embodiment a

sacrificial layer such as silicon oxide may be deposited
before the silicon nitride. There is then deposited over the
insulating layer 6 a thin film of a conductive material such
as gold. Alternatively the conductor may be deposited after
making the suspending microstructure. Standard optical
lithography is then used to pattern the wafer with the
elements of the sensor aligned in the (110) direction. A mask
is put down as shown by the shaded portions in Figures 6 to 8
which illustrate diagrammatically the shape of the mask for a
counterpart sensing element of Figure 1. Preferably all
corners are rounded to improve the mechanical properties of
the suspended sections. The mask is used to etch the
conductive layer in an etch of for example potassium iodide in
iodine and water. The insulating layer is then etched for
example using a plasma etch in carbon-tetra-fluoride and
oxygen. Then, the silicon substrate or the sacrificial layer
if there is one is etched. Where it is the silicon substrate
which is to be etched, the etch is carried out for example
using potassium hydroxide and water which etches silicon but
not silicon nitride or gold. The etch can be taken for
example to a depth of 20 microns. Where a silicon dioxide
sacrificial layer is used, a buffered hydrofluoric acid etch
is used for this step. Figure 4 shows a section through the
substrate after the conductive and insulating layers have been
etched and Figure 5 shows a section through the substrate
after the final etch. In particular, Figure 5 shows a
suspended element 14.

Figures 6 to 8 demonstrate how the final etch proceeds in the
case of silicon. Etching proceeds preferentially where there
are convex corners as identified by reference numerals 32
through 35 in Figure 7. Figure 2 shows a stepped portion
indicated by way of example by reference numeral 38 in the
legs of the sensing elements 14. These stepped portions
provide additional convex regions where the etch will occur
preferentially so that the etch process is speeded up. It
also reduces the depth required to etch into the wafer. These

stepped regions are not necessary where a sacrificial layer of oxide is used.

The sensor can be used in several different modes of operation. One example is the electrostatic mode.

A small potential difference (of the order of 1V) is maintained between contacts 12a and 12b. If a large potential difference (of the order of 20V) is applied between contacts 12a and 12c, there is an electric field resulting in an electrostatic attraction between the sensing elements 14a and 14c. As a result, the element 14a tends to move towards the element 14c and element 14c moves a similar distance towards element 14a by virtue of the symmetry of the sensor. Elements 14b and 14d do not move. The result is that the sensing tip 26a moves to reduce the gap between that tip and the tip 26b of the stationary element. For some sensing modes, the gap can be closed altogether. For stable operation, the width of the gap is set to be less than half the separation between elements 14a and 14c when there is no potential difference between contact regions 12a and 12c. For some applications the potential difference between the contacts 12a and 12c can be controlled so that sensing element 14a is not actually brought into contact with sensing element 14c.

The electrostatic mode of operation can for some applications be used by applying a potential difference between the contacts 12b and 12d. Sensing elements 14b and 14d then operate as described in relation to the sensing elements 14a and 14c, but in this case tip 26b moves to _increase_ the gap between the tip and the tip 26a of the stationary element.

An output from the sensor can then be derived in dependence on the electrical properties while the gap is closed. For example, the current flowing for a given applied test potential difference between 12a and 12b may be measured by circuitry connected to the contacts and implemented on the

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same silicon wafer. The test potential difference between 14a
and 14b is much smaller than the potential differences between
14a and 14c or 14b and 14d, and thus does not result in
significant movements of the suspended microstructures. In
another embodiment, where the sensing tips 26a,26b carry a
dielectric medium, a capacitor is formed between the sensing
tips when the gap is closed. This capacitance may be
measured. In yet another embodiment, a.c. excitation of the
sensing elements may be used to measure resonance properties,
for example make integrated resonators in place of the quartz
crystals presently used in watches, etc.

These and other modes of operating silicon sensors are
described for example in "Resonant Silicon Sensors" published
in Micromech. Microeng. 1 (1991) 113-125.

In a still further embodiment, the gap 28 need not be entirely
closed but merely closed to within a distance across which a
tunnelling current will flow between the sensing tips
26a,26b. An example of the use of the tunnelling effect in a
sensor is described in an article entitled "Fabrication of a
Tunnel Sensor with Cantilever Structure" published in the
Technical Digest of IVMC 19, Nagahama 1991, pages 204 and 205,
and in an article entitled "An electron tunnelling sensor" by
S.B. Waltman and W.J. Kaiser, published in Sensors and
Actuators 19(1989) 201-210.

When used as a tunnel sensor, the sensor of the present
invention has an advantage over known tunnel sensors in that
it can be manufactured on a single chip using technologies
compatible with CMOS and other integrated circuit processes.
Existing forms of tunnel junction devices use hybrid
technology and involve two or more chips which must be bonded
together. The problems arising from thin film stresses have
so far prevented the development of integrated single chip
tunnel sensors. As explained above, the effect of thin film
stresses are substantially ameliorated by the configuration of
the sensor described herein.

The sensor can be used as a gas sensor or pollutant sensor if the sensing portions 24a,24b of the suspended elements 14a,14b are coated with a layer of a substance appropriate to the analyte to be detected. The sensor of the present invention lends itself readily to coating with suitable layers by evaporation after it has been fabricated. In known sensors, the sensing gap is often formed between a point structure in a lower plane and a continuous structure in an upper plane. It is then necessary to coat the underside of the upper structure, which can be awkward. When the sensor is used in this way, the gap can be left open during exposure to the gas and then closed electrostatically (by applying a voltage between 12a and 12c) when a readout is required. The absorption of the gas onto the film deposited on the sensing portions changes the resistive, capacitive or other electric properties measured at the contacts using a test potential between 12a and 12b as described above. After a reading has been taken, the gap can then be reopened for a further sensing period.

Figure 3 shows a modified embodiment of the present invention which can be used as an accelerometer. In this embodiment, the sensor is formed in substantially the same way as described with reference to Figures 1 and 2 but a mass 30 is added to the sensing portion 24b of the sensing element 12b. The mass 30 is simply an extra piece of the materials of the suspended element in which case the fabrication process is the same as the method of manufacture described above in relation to Figures 4 to 8. If the substrate undergoes an acceleration downwards in Figure 3, the mass 30 is subject to a force which causes the gap 28 to decrease in size and the tunnel current is increased exponentially with the gap width. In order to obtain a measurement, a voltage can be applied to the contact 12d to create an electrostatic attraction pulling the element 14b towards the element 14d so as to maintain the gap at a constant size. The readout from the sensor is then the voltage applied to the contact, this voltage being directly

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proportional to the acceleration. The component of
acceleration in the direction to the left in Figure 3 could be
detected by a similar sensor oriented at 90° with respect to
that in Figure 3, and manufactured on the same substrate.

Figure 9 shows a modified embodiment of the invention which
can be considered as a modified version of Figure 1 in which
the sensing element 14c carries a sensing portion 24c in place
of the sensing element 14a. The sensing element 14a is then
integral with the sensing element 14d. This thus provides a
reference beam 22 formed by the return legs of the sensing
elements 14a, 14d. Thus, an electric current can flow between
the contacts 12a and 12d. Each sensing portion 24b,24c
defines with the beam 22 a respective sensing gap 29,30. If a
magnetic field is applied perpendicular to the plane of the
paper and a current, e.g. of the order of mA, is passed
through the beam 22, the long beam 22 is deflected by a
Lorentz force in the plane of the paper Detection is by
making or breaking a tunnel contact across the sensing gap 29
or 30, and detecting the current at the support region
12b,12c. This current could be of the order of nA.

In the accompanying drawings, the sensing elements are shown
with sharp corners for the sake of diagrammatic simplicity.
In practice, rounding of the corners in the suspended section
improves the mechanical properties of the sensor.

The present invention can also be used to implement a
plurality of sensors on a common substrate, one above
another. That is, after forming a sensor as described herein,
a further sensor could be manufactured atop the first sensor.
For example, a sensor in one plane could have a sensing gap in
the x direction while the sensor in the next plane could have
a sensing gap in the y direction perpendicular to the x
direction.

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For the sake of completeness reference is also made to an
article reviewing the state of the art in tunnelling sensors
in 1988 entitled "Scanning tunnelling engineering" published
in the Journal of Microscopy, Vol. 152, Pt. 2, November 1988,
pages 585-596.

CLAIMS:

1.   A micromechanical sensor comprising a plurality of
sensing elements supported on a substrate at respective
support regions, a first set of said sensing elements having
respective sensing portions and arranged to define a sensing
gap and a second set of said sensing elements forming a
counterpart set, the sensing elements being substantially
similar one to another, and each sensing element comprising an
outgoing elongate leg extending away from its associated
support region and a return leg substantially parallel to the
outgoing leg extending towards the support region.

2.   A micromechanical sensor according to claim 1 wherein the
support regions are arranged symmetrically on the substrate.

3.   A micromechanical sensor according to claim 1 or 2
wherein the support regions are arranged in close proximity to
one another and to the sensing gap.

4.   A micromechanical sensor according to any preceding
claim, wherein the first set of sensing elements comprises
sensing elements supported by adjacent support regions, the
return leg of each sensing element terminating in its sensing
portion and the sensing portions defining between them the
sensing gap, and wherein the second set of sensing elements
comprises elements supported by adjacent support regions, the
support regions supporting the sensing elements of the second
set being arranged opposite the support regions supporting the
sensing elements of the first set, whereby one of the second
set of sensing elements acts as a control element to attract
one of the first set of sensing elements and thereby close the
sensing gap.

5. A micromechanical sensor according to claim 1, 2 or 3 wherein the first set of sensing elements comprises sensing elements supported by support regions diametrically opposed with respect to one another, the free ends of the return legs of the sensing elements carrying the sensing portions and wherein the counterpart sensing elements are supported by respective support regions also arranged diametrically opposed to one another and perpendicularly with respect to the support regions supporting the sensing elements of the first set, the return legs of the sensing elements of the counterpart set being connected to form a suspended beam, which acts as a reference element with which each sensing portion defines a sensing gap.

6. A micromechanical sensor according to claim 1, 2, 3 or 4 wherein one of the first set of sensing elements carries a proof mass.

7. A micromechanical sensor according to any preceding claim wherein each leg of each sensing element includes a stepped region, the stepped regions being arranged so as to maintain the similarity of the sensing elements and lying in the plane of the sensing element.

8. A micromechanical sensor according to any preceding claim wherein each sensing element comprises an insulating layer and a conductive layer over the insulating layer.

9. A micromechanical sensor according to any preceding claims wherein the sensing portions can be provided with at least one additional sensing layer particular to an analyte to be sensed.
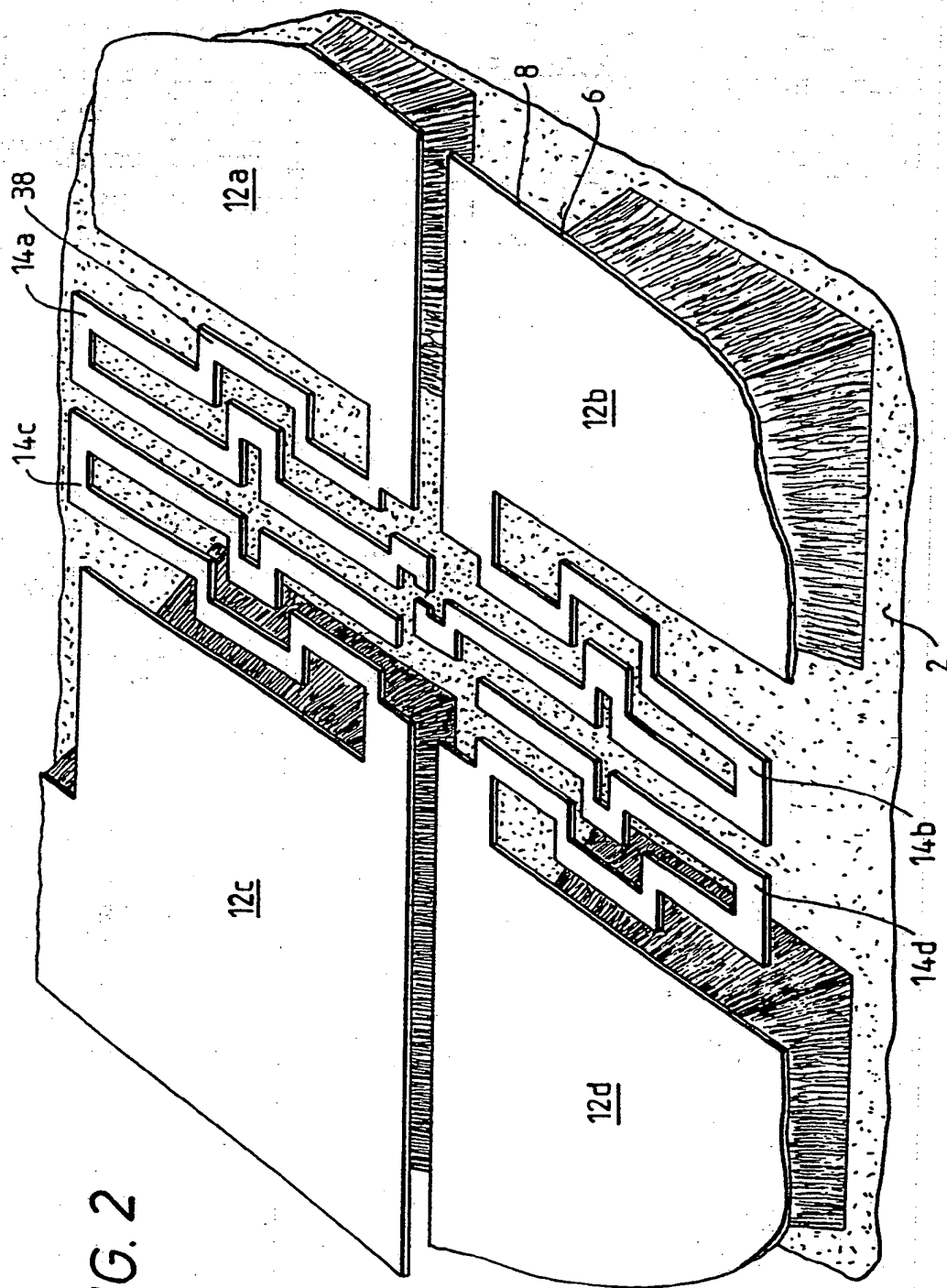
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FIG.1

FIG. 3

FIG.4

FIG.5
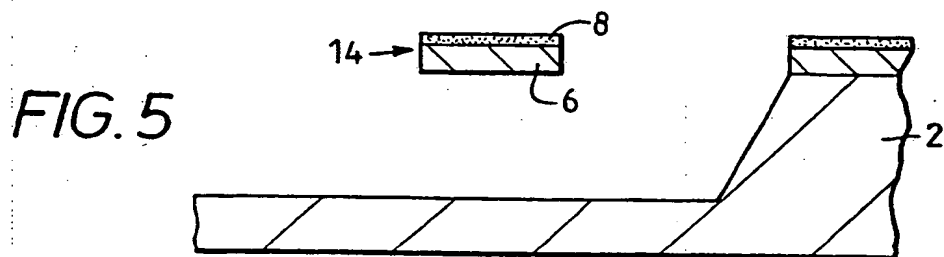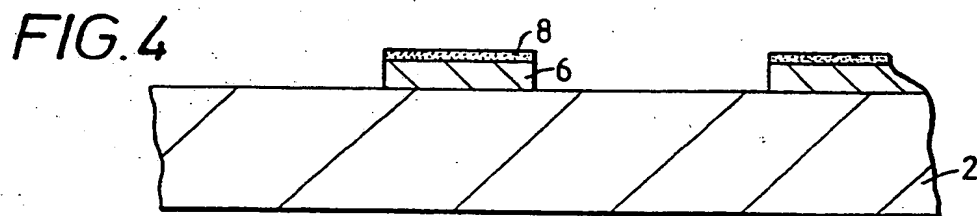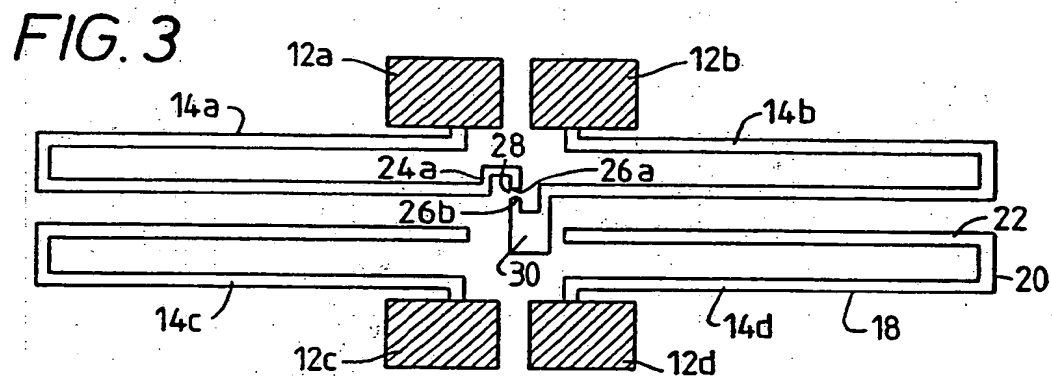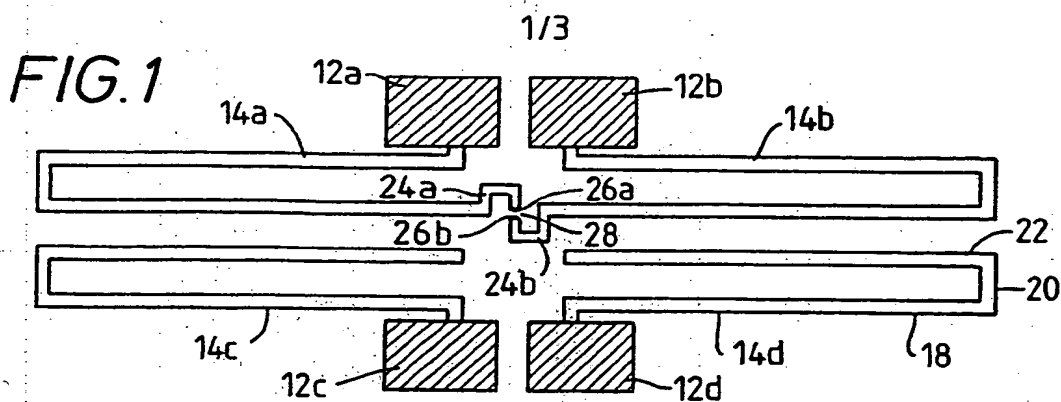
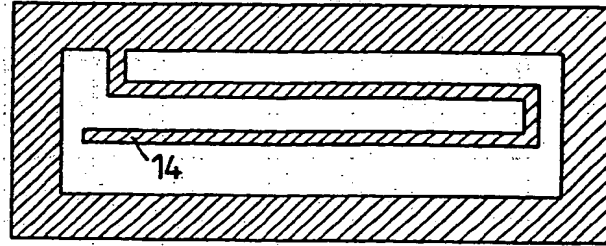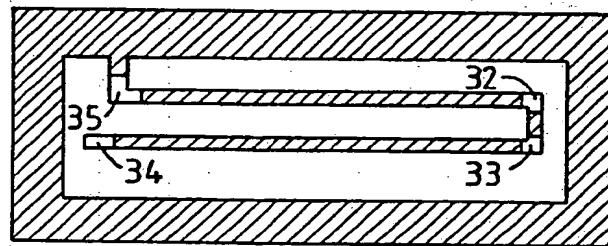SUBSTITUTE SHEET
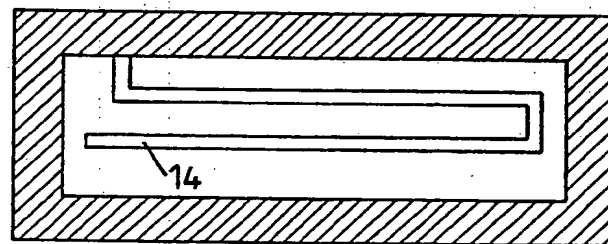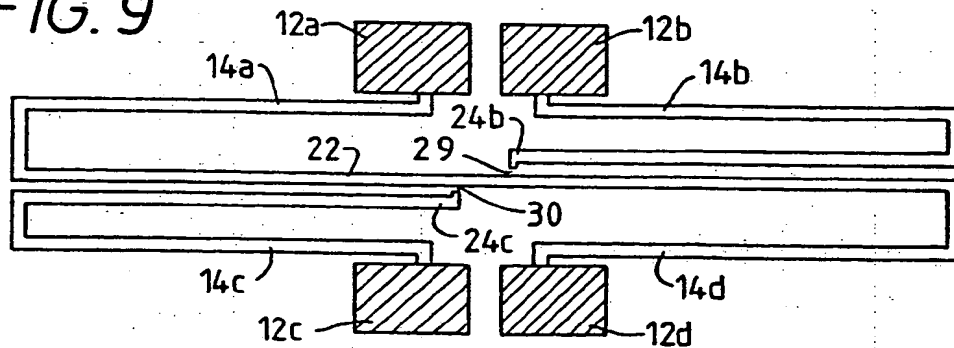
FIG. 2

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FIG.6

FIG.7

FIG.8

FIG.9

SUBSTITUTE SHEET

INTERNATIONAL SEARCH REPORT

International Application No | PCT/GB 93/00532

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all)[6]

According to International Patent Classification (IPC) or to both National Classification and IPC

Int.Cl. 5 G01B7/14;   G01P15/08;   G01B7/00

II. FIELDS SEARCHED

Minimum Documentation Searched[7]

Classification System	Classification Symbols
Int.Cl. 5	G01B ; G01P

Documentation Searched other than Minimum Documentation
to the Extent that such Documents are Included in the Fields Searched[8]

III. DOCUMENTS CONSIDERED TO BE RELEVANT[9]

Category [o]	Citation of Document,[11] with indication, where appropriate, of the relevant passages[12]	Relevant to Claim No.[13]
X	WO,A,9 203 740 (ANALOG DEVICES INC) 5 March 1992	1,2,3
Y	see page 10, line 14 - page 17, line 11; figures 4-8	4,6-9
A		5

Y	APPLIED PHYSICS LETTERS. vol. 58, no. 7, January 1991, NEW YORK US pages 100 - 102 T.W.KENNY ET AL 'micromachined silicon tunnel sensor for motion detection'	4,7,8

Y	JOURNAL OF VACUUM SCIENCE AND TECHNOLOGY: PART A. vol. 8, no. 4, July 1990, NEW YORK US pages 3606 - 3613 D.W.BURNS ; H.GUCKEL 'thin films for micromechanical sensors'	6
A		1

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° Special categories of cited documents :[10]

"A" document defining the general state of the art which is not considered to be of particular relevance

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search

28 JUNE 1993

Date of Mailing of this International Search Report

0 7. 07. 93

International Searching Authority

EUROPEAN PATENT OFFICE

Signature of Authorized Officer

BROCK T.J.

Form PCT/ISA/210 (second sheet) (January 1985)

III. DOCUMENTS CONSIDERED TO BE RELEVANT (CONTINUED FROM THE SECOND SHEET)

Category°	Citation of Document, with indication, where appropriate, of the relevant passages	Relevant to Claim No.
Y	US,A,4 953 387 (C.L.JOHNSON ET AL) 4 September 1990 see the whole document ---	9
A	EP,A,0 149 572 (COMMISSARIAT A L'ENERGIE ATOMIQUE) 24 July 1985 see the whole document ---	1-3,6,8
A	JOURNAL OF MICROMECHANICAL ENGINEERING vol. 1, 1991, pages 113 - 125 G.STEMME 'resonant silicon sensors' cited in the application ---	1
A	JOURNAL OF MICROSCOPY vol. 152, no. 2, November 1988, pages 585 - 596 C.SCHNEIKER ET AL 'scanning tunneling engineering' cited in the application ---	1
A	US,A,4 783 237 (H.E.AINE ; B.BLOCK) 8 November 1988 see the whole document -----	1

ANNEX TO THE INTERNATIONAL SEARCH REPORT
ON INTERNATIONAL PATENT APPLICATION NO.

GB 9300532
SA 71782

Patent document cited in search report	Publication date	Patent family member(s)		Publication date
WO-A-9203740	05-03-92	EP-A-	0543901	02-06-93
		JP-T-	4504003	16-07-92
US-A-4953387	04-09-90	None		
EP-A-0149572	24-07-85	FR-A-	2558263	19-07-85
		CA-A-	1251338	21-03-89
		DE-A-	3566459	29-12-88
		JP-A-	60159658	21-08-85
		US-A-	4653326	31-03-87
US-A-4783237	08-11-88	None		

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FIG.1

12a — [hatched block]   [hatched block] — 12b
14a   14b
24a — | 26a
26b — | 28
24b
22
20
14c   14d   18
12c — [hatched block]   [hatched block] — 12d

FIG.3

12a — [hatched block]   [hatched block] — 12b
14a   28   14b
24a — | 26a
26b — |
30
22
20
14c   14d   18
12c — [hatched block]   [hatched block] — 12d

FIG.4

8
6
2

FIG.5

14 →   8
6
2

FIG. 2

FIG. 6

FIG. 7

FIG. 8

FIG. 9